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Integrating Survivability into 21st Century Design

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Director's Notes

Aircraft design and development is a very complex process requiring many years and a lot of money to produce a useable product. Many tend to focus only on the cost and schedule numbers of a program rather than on the accomplishment of producing a highly capable and technically advanced aircraft. But behind those volumes of numbers, viewgraphs, spreadsheets, and documents are numerous highly qualified acquisition professionals who are working diligently to master the art of aircraft acquisition. Yes, the "art" of aircraft acquisition. Behind all the cost, schedule, and performance numbers are program offices working to juggle all the desired requirements of the warfighter and the cost constraints of congress. There are multitudes of trades. Some are conducted at the mission level, determining what role the aircraft should ultimately play, while others are at the lowest levels in aircraft design, determining where to put a certain component or wire bundle. This issue of the newsletter looks at one aspect of aircraft design, survivability, and the many different factors affecting how survivability is built into aircraft design.

Aircraft design and development has certainly changed in recent years. In the old days, the government defined the requirements from the system down to the component level, essentially telling the contractor how to build it. Now, we are embracing performance based requirements and spiral development and the contractor has almost complete oversight of the aircraft design. The good news is that with spiral development, there are many more technology insertion points into the acquisition process. Before, survivability enhancements had to be designed in early or else they would have little chance of getting on the aircraft. This is still the best point to get most vulnerability reduction designed into the aircraft. However, we have the flexibility of adding survivability upgrades into a block upgrade in the spiral development process. In contrast, we now sell our survivability upgrades to the contractor vice the program manager. Of course, the PM ultimately has to sign off on any upgrades, but we still need to convince the contractor of the worth of any added survivability features. It's a significant shift in the way we do business.

This issue of *Aircraft Survivability* provides a glimpse into some of the factors considered when designing survivability into modern day aircraft. RDML Heely illustrates the new importance placed on information management capabilities in aircraft systems. An aircraft must not only be able to conduct combat missions, but also able to gather information. Does anyone remember what the F–22 and the RAH–66 were originally intended for? Well, now they are being touted as future information/sensor platforms that will be used to supply all combat participants with information. Another article by Sean Townsend, describes some of the work being done to counter a future threat—the Anti-Helicopter Mine. This is an excellent example of how aircraft designers must not only be able to design an aircraft to respond to a current threat, but also anticipate future threats.

Just a couple of months ago some of our aircraft were involved in some pretty intense combat action during Operation Anaconda. We have re-printed an article from the *Army Times* about the superb performance of the Apache aircrew and aircraft under extraordinary conditions. This article illustrates the bottom line in aircraft survivability—to design aircraft that provides our aircrews with a platform to effectively accomplish their missions and return them home safely. Once these aircraft arrive home, the aircraft survivability community is just beginning their work. LTC Tony Brindisi describes how combat data collection is an integral part of overall aircraft survivability design discipline. We can learn much about aircraft survivability by examining actual combat damage on an aircraft. This information can then be fed back to the aircraft designers to learn what worked and what didn't. It also allows the designer to make adjustments in upgrades or future aircraft.

Lastly, this issue also includes the inaugural article on "Young Engineers in Survivability." This is one way to let people know who is responsible for bringing our brave aircrews, like those that flew the Apaches in Afghanistan, home safely.

Hopefully, this issue of the newsletter will lend some insight into all the diverse and complicated factors that go into aircraft design. Although we only focus on survivability considerations, one can only imagine how the complexity of designing a modern day aircraft can quickly increase exponentially. That is why I say that aircraft design is truly an art. ◆

LCDR Andrew (Andy) Cibula (USN)
Director, JTCG/AS Central Office

Network Centric Warfare as a Survivability Enhancer

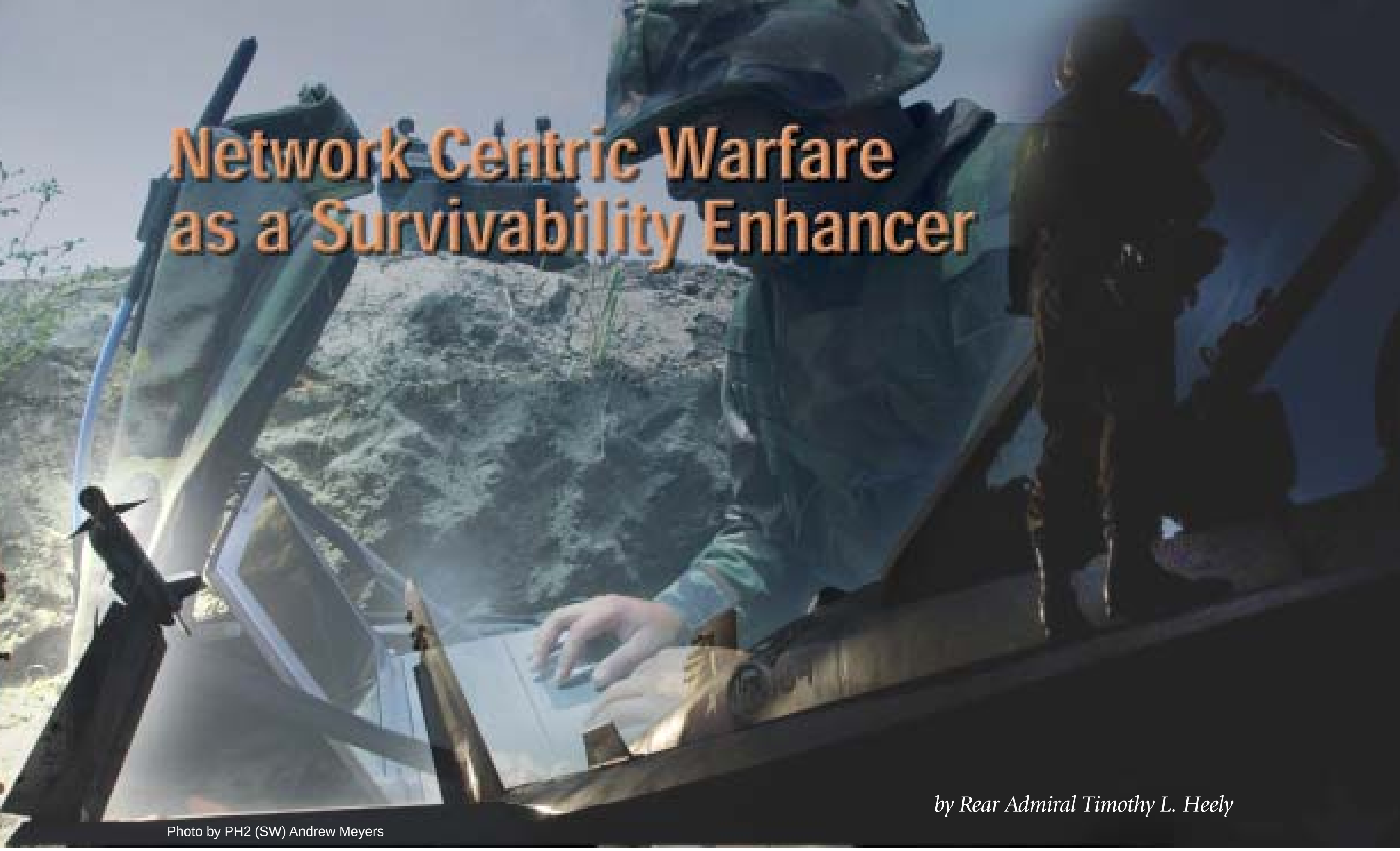

Photo by PH2 (SW) Andrew Meyers

by Rear Admiral Timothy L. Heely

To attain the operational objective of Full Spectrum Dominance, Joint Vision 2010 and 2020 has identified dominant maneuver, precision engagement, focused logistics, and full dimensional protection as the four critical operational vectors. The key to focusing these vectors is information superiority. This information superiority, essential to successful implementation of the Joint Vision, is enabled through the sharing of information over a network architecture—a Battle group FORCEnet. But even as we address the concept of FORCEnet and how it will be included in future weapons systems, we must find ways to ensure our aging systems receive the necessary avionics improvements and survivability upgrades to maintain their operational relevance.

FORCEnet is a derivative of network centric warfare (NCW), and it will position naval aviation to advance the speed and accuracy of tactical operations in a network centric environment. FORCEnet is the architecture and building block of sensors, networks, decision aids, weapons, warriors, and supporting systems integrated into a highly adaptive, human-centric, comprehensive system that operates from seabed to space, from sea to land. NCW is the overarching transformational concept where information is transformed into advanced combat power. These concepts will transform information superiority into combat power by effectively linking knowledgeable entities in the battlespace. This will extend the power, reach and precision of our Naval and Joint Forces. Future platforms and legacy platforms, will have operational relevancy only to the extent that they can provide information to, and extract the required tactical information from, the applicable sensor, communication, or shooter grid. Survivability improvements will come when we process the wealth of available threat data in a timely and effective fashion.

Future aircraft will have interoperability and connectivity designed in from the start. They will increase our strike capability through their own increased lethality, but will also provide a force multiplier effect for legacy aircraft through their ability to share situational awareness data and provide off-board cues to Battle Group assets. Also, their ability to transmit maintenance data regarding the health and status of on-board systems will ensure rapid turnarounds to maximize sortie generation,

and thus will provide an incredible survivability improvement to all battle group assets.

Although legacy aircraft will present one of the greatest challenges to the implementation of NCW, this is a challenge we must, and will meet. Integrating the capabilities of NCW into these legacy aircraft, with their limited processing capabilities and older avionics system architectures pose a problem. This problem, however, is already being addressed by such platforms as the F/A–18. The communication, sensor data link, and data management systems necessary to make the platform an active recipient and contributor of NCW data have been identified. The Naval Aviation Core Avionics Master Plan has been established and it identifies the joint technical architecture connectivity requirements. This Master Plan serves as the Naval roadmap to interoperability and NCW—it is designed to provide a coherent acquisition strategy to achieve commonality and NCW interoperability in the near future.

Network cueing and targeting, made possible through NCW, will be critical to address the battle problem of mobile targets. To attain this capability of time critical strike in order to counteract the enemy's ability to "shoot and scoot" and then shoot again, we will need weapon systems capable of rapidly destroying targets with absolute precision throughout the entire battle space, while complying with rules of engagement, resource optimization, battle force coordination, rapid response, and decentralized execution.

One way to do this is by using long range stand-off precision weapons. This will not only provide the necessary accuracy, but will shift most of the survivability burden from the aircraft to the weapon itself, and will allow the aircraft and its crew to remain outside of lethal threat envelopes.

Unmanned air vehicles (UAVs) will also be used in a sensor mode to gain target data as well as eventually counteracting the threats themselves, thus providing even greater survivability benefits to our Naval forces. These UAVs will add a depth and complexity to our battle tactics never seen before, and not fully realized. Their full integration into the NCW grid along with conventional airborne assets will be absolutely essential to ensure our maximum striking capability along with our minimum risk to survivability.

The 21st Century United States Naval forces must be equipped to exploit the vast array of information warfare assets in a real-time fashion. We will have an assortment of precision

Photo by Tech SGT. Joe Springfield & PH2 (SW) Andrew Meyers

Photo by PH2 (SW) Andrew Meyers

stand-off weapons exhibiting pin-point accuracy with extremely high lethality. A time-critical strike capability will result in acquiring, classifying, targeting, and executing tactical strikes before the enemy can respond. We will transform from today's conventional flight deck load of Tomcats, Hornets, and Prowlers to flight decks packed with Super Hornets, the Joint Strike Fighter, Advanced Electronic Attack Platforms, and UAVs. Through the combination of these aircraft, and the almost unimaginable possibilities that a fully integrated NCW will permit, our Naval force will prove to be even more survivable and lethal, and provide our nation a dominant power projection capability anywhere in the world. ◆

Rear Admiral Tim Heely graduated from the United States Naval Academy in 1975 with a Bachelor of Science degree in American Political Systems and later earned a Master of Science Degree in Aeronautical Engineering from the Naval Postgraduate School.

He flew the A–7E Corsair II and the FA–18C Hornet from Naval Air Stations in California and Japan, and aircraft carriers in the Pacific and Indian Oceans. He commanded Strike Fighter Squadron 192's World Famous Golden Dragons and has logged over 3500 flight hours, 850 carrier arrestments, and flown combat missions over Kuwait and Iraq during the Gulf War.

Rear Admiral Heely served as Deputy Class Desk Officer on the A–12 program, Head Aviation Commander Detailer at the Bureau of Naval Personnel, Class Desk Officer and Deputy Program Manager of the F/A–18A/B/C/D program and Program Manager for Naval Undergraduate Flight Training Systems. In August 2000, he was selected to Flag rank and his current positions of Commander, Naval Air Warfare Center Aircraft Division and Assistant Commander for Research and Engineering, Naval Air Systems Command.

Photo by CWO2 William D. Crow

UAVs and Combat Survivability

by Rear Admiral Robert H. Gormley, U.S. Navy (Ret)

Reports from the war in Afghanistan point to unmanned aerial vehicles (UAV) as one of three principal contributors to the success of the U.S. campaign to root out the Taliban and Al Qaeda terrorist elements, the others being special operations forces and precision weapons. The benefits and promise offered by UAVs in surveillance, targeting and attack have captured the attention of senior Defense Department officials, members of Congress, and the public alike. Indeed, operations in Afghanistan appear to confirm that unmanned air systems have come of age.

As with most new military concepts, the path to acceptance of UAVs and recognition of their worth has been long and not without obstacles. Unmanned aircraft as target vehicles and air-to-surface weapons date back many years and were employed in World War II. For intelligence, surveillance and reconnaissance (ISR), camera-equipped Ryan Firebee drones enjoyed great success during the Vietnam War, flying some 3,400 sorties over heavily defended North Vietnam. But despite the promise of early experiments and operational deployments, the U.S. Military has, until recently, been slow to invest in UAV development and reluctant to incorporate unmanned systems into the regular force structure. Looking back, it appears that earlier introduction of UAVs was impeded by several factors—culture, immature technologies, and a general lack of recognition by advocates that unmanned systems demand aerospace-quality treatment in design and manufacture.

Over the past several years, however, a confluence of events and developments has brought about a marked change in how the military worth of UAVs is perceived by operational commanders and senior DoD civilian officials—

- Advances in sensor technology that make possible reduced sensor size and weight, provide high resolution, and permit detection of fixed and moving targets under a variety of environmental conditions.
- Dramatic increases in computer processing power.
- Improved communications, imagery processing, and imagery exploitation capabilities.
- Increased recognition by UAV advocates in industry and government that a model airplane, "hobby shop" approach to development will not yield reliable and military-useful unmanned air systems. Aerospace-quality expertise is essential.
- Emergence of the requirement for continuous surveillance of the battlespace, providing commanders with what is, in effect, a low hanging, stationary satellite. Hence, the quest for long endurance UAV systems that, if manned, would tax or exceed the limits of human endurance.
- Availability of robust, long endurance UAV platforms resulting from visionary investments by the Defense Advanced Research Projects Agency (DARPA) and the DoD in the 1980s and 1990s—Amber, Predator, and Global Hawk—sometimes in the face of resistance from the Military Services.
- Pressure on the Military by political authorities and the general public to minimize casualties and capture of aircrews by the enemy.
- The generally high marks accorded Predator and Hunter during Operation Allied Force in the 1999 air war against Serbia and recently to Predator and Global Hawk during Operation Enduring Freedom in Afghanistan.

UAVs have been identified as "transformational" by President Bush and the DoD leadership and, as a consequence, this high level of interest is reflected in budget numbers and programs of the Military Services. Overall, Defense Department plans show a $1.1 billion investment in UAVs for Fiscal Year 2003, divided equally between procurement and R&D, up some 13 percent from FY02. Importantly, the Air Force has committed to increased production rates for Predator and Global Hawk, the Navy has put money on the line for Global Hawk, and the Army is moving ahead with its Shadow 200 tactical system. Further, DARPA is pursuing a number of UAV advanced technology demonstrations in concert with the Military Services—fighter-like air vehicles for lethal missions, rotorcraft for attack and long

endurance ISR, and small or micro-UAVs for urban combat. Thus, as production rates ramp up and technology demonstrations prove successful, we may expect to see dramatically increased monies showing on the UAV line in future defense budgets.

What about survivability of UAVs in combat? Does it merit more attention? During the 1999 war in Serbia, allied forces lost some 20-25 unmanned aerial vehicles, among them Predators, Hunters, and French/German CL-289s. Two Predators were lost in operations over Iraq this past year and five in Afghanistan as of early 2002. The cause of a loss, by hostile fire or accident, is sometimes unknown when an air vehicle disappears or fails to return to base. But notwithstanding the cause, it seems clear that both regular military forces and paramilitary groups worldwide are aware of the threat posed by UAVs and will seek to shoot them down or otherwise degrade their mission effectiveness.

In the past, UAV advocates gave minimal consideration to survivability, and in some cases to the need for reliability, with the view being that UAVs were to be cheap, and thus, expendable. What really counted most in the thinking of proponents was that aircrews are not put at risk when UAVs carry out dangerous missions. It followed that, with the exception of the now-cancelled DarkStar and its classified program predecessors, combat survivability was not a driving operational requirement. As a consequence, the survivability characteristics typical of manned military aircraft have not been accorded a regular seat at the UAV platform design table. Here we are talking about basic survivability elements—redundancy and separation of critical components, reduced signatures (RF, IR, visual, acoustic), fire and explosion mitigation, countermeasures, and reliable subsystems and components.

As warfighting commanders have had the opportunity to operate UAVs in combat, see the benefits offered, and suffer occasional disruptive losses, survivability has become a matter meriting serious attention, and for two principal reasons. First, the kinds of UAVs that operational commanders want are not cheap and, in fact, are likely to become more costly as demanded capabilities are added. For example, today's Predator costs about $4 million and Global Hawk more than $20 million if equipped with their original payloads and in quantity production. These figures will grow considerably as new, more sophisticated payload elements and air vehicle performance enhancements are added to later production blocks. So, with unit costs such as these, the totals are not inconsequential when one adds up losses attributable to combat shoot downs and accidents. Even for small tactical UAVs, the tab can be significant since they operate in hazardous low altitude battlespace, usually at slow airspeeds, and may well carry expensive sensors.

A second reason for heightened interest in UAV combat survivability has to do with preventing the denial, to the warfighter, of crucial surveillance or attack capabilities. For example, if an ISR UAV system is as successful as its advocates would like, operational commanders will then become dependent on it for key tactical information. Thus, a shoot down will interrupt the flow of ISR and targeting assistance, perhaps at a critical time. The choices, then, are to make such UAVs more survivable, which will increase unit cost, or to buy "extra" low cost, non-survivable systems and provide airborne spares that can move in quickly to plug an ISR coverage gap. This is, of course, the classic trades analysis which must be done to determine the crossover point between fielding survivable, but more costly UAVs, or buying cheaper, less survivable vehicles in greater numbers.

To improve combat survivability of UAVs, it makes sense to apply survivability techniques and technologies from the manned aircraft world. However, some survivability elements merit special attention when determining if it is cost-beneficial to apply them to a given UAV system, viz—

- **Signature reduction.** It is here that the greatest survivability emphasis is likely to be placed, and RF, IR, visual, and acoustic signatures must all be considered. For example, even small UAVs can have large RF signatures. And also, there are sound detection systems which can detect a UAV with an acoustic signature that falls outside the hearing range of the human ear.
- **Vulnerability reduction (damage tolerance).** Making UAVs more damage tolerant should be part of the design trades process. However, the degree of attention to be devoted to vulnerability reduction is a function of air vehicle size and cost, and its planned operating environment. Hence, some vulnerability

Photo by PH3 Jennifer A. Smith

reduction features are unlikely to prove cost effective if a UAV is small and the basic platform low in cost.

- **Sensor performance**. For ISR UAV systems, the trade between imagery resolution and standoff distance is the name of the game. Thus, overall survivability trades must include mission sensor power requirements and aperture size as they affect distance from an imagery target and nearby threats, as well as safe flight altitude.
- **Weather**. The ability of an air vehicle to operate in or above the weather, thereby avoiding low altitude flight under clouds, bears greatly on its combat survivability.
- **Tactics**. Commanders seek long dwell, continuous surveillance of the battlespace. Depending on the threat level, however, a loitering UAV, no matter how stealthy, may not long avoid detection. It follows that the tactics to be employed are crucial.
- **Command control, ISR data links, and GPS.** These must be considered since, more so than with manned aircraft, they are essential to UAV flight safety and mission success.

It is now widely accepted that UAVs are here to stay and have much to offer warfighting commanders in executing so-called "dull, dirty and dangerous" missions. While the precise manner in which these systems will be employed in every circumstance is still evolving, it is clear they are assured a prominent place in the world's armed forces in the future. Currently the U.S. Military is developing unmanned air systems and operational concepts for both ISR and lethal missions. Members of Congress and the DoD's civilian leaders have placed a high priority on UAVs and, consequently, their number and capabilities will increase dramatically over the next decade. And because of cost and the significant military worth now accorded UAVs, their combat survivability must become integral to the system design and upgrade process, as is the case with manned aircraft. Only if survivability is given serious consideration can the true potential of unmanned air systems be fully realized. ◆

RADM Robert H. Gormley USN, (Ret), is Chairman of the Combat Survivability Division of the National Defense Industrial Association (NDIA). He is also President of The Oceanus Company and a Senior Vice President of Washington-based Projects International, Inc. He resides in Menlo Park, California and may be reached at 650.854.8155.

Combat Data Collection

by Lt Col Anthony E. Brindisi, Mr. John M. Vice, and Mr. Donald Voyls

JTCG/AS Sponsored Project

Many different types of intelligence data are routinely collected during combat. However, one of the most frequently overlooked types is the perishable data that should be collected when aircraft are damaged or lost. These data are invaluable. As Lt Col Ronald Terry, Director of the AC–130 Gunship Program during Vietnam stated, "BDART (Battle Damage Assessment and Reporting Team, the combat data collection team at that time) data has been useful in many ways. In one particular incident we took a hit in an area that had an inordinate damage to the aircraft and secondary damage to personnel and equipment. Through the information gained and the analysis of this particular hit we were able to put certain designs on board the aircraft such that sometime later we took another hit in somewhat the same place that resulted in no damage to the aircraft, on-board equipment or personnel."

There were many other similar situations during the Southeast Asia conflict. During that period, DoD found that by collecting and analyzing every aspect of combat damage to U.S. aircraft, trends emerged pointing to aircraft vulnerabilities. Over the course of the conflict, many vulnerability reduction modifications were performed on aircraft of all types leading to the ability of U.S. aircraft to absorb more punishment and still bring their aircrews either all the way home or much closer, preventing hundreds of airmen from becoming prisoners of war. Modifications such as self-sealing fuel tanks, control system separation and redundancy, electronic countermeasures and armoring flight critical components were rushed into service. The AC–130 is but one example of what was done. Non-materiel changes to doctrine and tactics were also made, changing the manner in which we employed the aircraft so as not to be engaged and damaged by the enemy.

So what is combat data collection? Briefly stated, it is the systematic collection of every possible aspect of a battle damaged aircraft's mission to include the pre-mission intelligence brief, through the actual sortie (including the combat damage or loss encounter), aircrew accounts of the threat engagement, and the thorough documentation of the final disposition of the aircraft, whether it be repaired or salvaged. It is important to be able to understand what happened and what can be learned from the incident about aircraft susceptibility and vulnerability. There were over 4,500 documented incidents of aircraft damages and losses during the Vietnam conflict among all Services involving both fixed and rotary wing aircraft. This information was the basis, not only for the rapid modifications to combat aircraft, but it formed the bedrock of knowledge we have used in the design of all aircraft since.

Once the Vietnam conflict concluded, the combat data collection capability of DoD quickly atrophied. During the conflicts in Panama, Grenada, and Libya, there was no one close to the action to document what had happened to our aircraft during combat. An effort was made to reconstruct the data after the fact, however,

Figure 1. Combat damage

the results were hit and miss. When Operation Desert Storm commenced, several combat data collection teams were assembled and trained, but none was permitted in theater to perform real-time data collection. Once again, the task was left to post-conflict reconstruction, again with mixed results. The lesson learned is that in order to get as complete a data set as possible, real-time data collection is a must!

During the early 1990s, the Air Force Research Laboratory addressed the issue of combat data collection. They had learned the value of the data collection efforts and realized that, although they had a comprehensive database based on the Vietnam experience, aircraft, threat systems, and tactics had evolved since then, and there was no process to update the existing database. Ultimately, they developed an Air Force Reserve team tasked with the collection of threat-induced combat damage data. Furthermore, in order to sustain the team during the periods between conflicts, the Air Defense Lethality Team would take on the mission to synthesize the data available in the Survivability/Vulnerability Information Analysis Center (SURVIAC) archives and develop a Threat Warheads Effects Training Program. The team's focus is on the "business end of the threat." The team integrates information on threat lethality/aircraft vulnerability from combat, live fire testing, and threat exploitation in order to influence mission planning, tactics, damage assessment and to provide data for weapon system upgrades and future designs. The Team's mission is to—

- Enhance combat aviation readiness for threat awareness and damage to aircraft
  - Collect and analyze data from combat damages and losses
    - Identify threat weapon system causing damage
    - Determine damage mechanisms
    - Compile complete record for detailed analyses
- Improve effectiveness of operations and maintenance support to combat operations
  - Understand lethality of threat projectiles and missiles
  - Integrate information to assess threat
  - Embed threat lethality in tactics
  - Assess damaged aircraft efficiently/effectively
- Guide Science and Technology (S&T), JTCG/AS, and Live Fire Test investments for

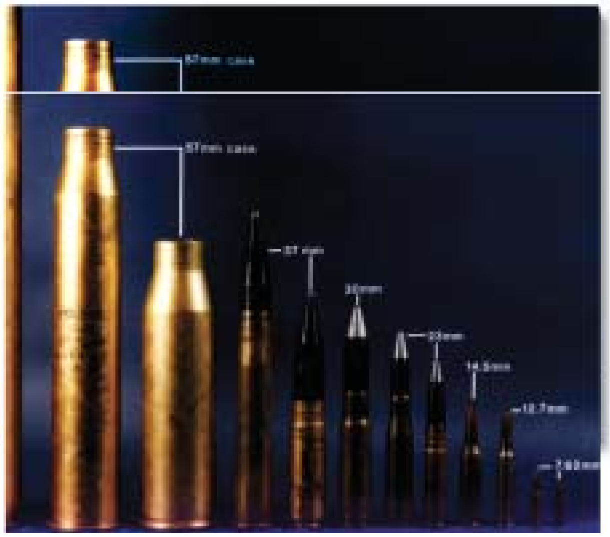

Figure 2. Munition hardware

During Operation Allied Force, this team captured much of the Air Forces' combat damage data. It was through a combination of near-real-time and post-conflict reconstruction that the data were collected and comprehensive case files were assembled and are available at SURVIAC.

The JTCG/AS, a long time supporter and user of combat data, recognized the team's value to all the Services and sponsors many of the Team's efforts. Under the JTCG/AS's mentorship, bridges were built between all three services in order to develop Tri-Service combat data collection capability, and the team's name was changed to the Joint Service Air Defenses Lethality Team. Currently the team is made up of reservists from Air Force Materiel Command's 46 OG/OGM/OL–AC at Wright-Patterson AFB, OH; Naval Air Systems Command, Patuxent River, Maryland, Office of Naval Intelligence/SPEAR, Washington D.C.; Naval Air Warfare Center, China Lake, CA and the Army's Aberdeen Test Center. The teaming between the components is growing and a true "purple" capability is emerging, providing a strong and diverse combat data collection force.

The value of the perishable combat data collection is unchallenged; ask any aircrew member who has successfully flown a combat damaged aircraft home. Detailed aircraft combat damage, vulnerability, and loss data is vital for aircraft entering the acquisition cycle. War planners need this data to anticipate aircraft sortie generation rates, aircraft loss rates, and predict the amount of spares/repair materials required to serve the National interest. Though many ways have been tried, experience has shown that combat data collected by an expert team, on the scene, is the only way to maximize collection of this data that is so enormously valuable to all concerned. The trained and ready Joint Service Air Defense Lethality Team (JSADLT) and the JTCG/AS connection to the warfighter, continues to provide the Service's combat data collection capability. However, it is only through the support of all those who develop, build, procure, support, and fly combat aircraft that it can be insured the JSADLT is at the right place at the right time collecting the right data that is so precious to so many. ◆

For additional details on the Team, please contact the Team leader, Lt Col Anthony E. Brindisi, USAFR, at anthony.brindisi2@wpafb.af.mil. Lt Col Anthony E. Brindisi is the senior reservist for the 46th Test Wing at WPAFB, Ohio. His B.S. degree is from Parks College of Aeronautical Technology and he holds an M.S. from the University of Southern California. In his civilian life, Tony has over 20 years of aircraft susceptibility reduction experience, primarily as a Low Observables engineer working both in industry and for the Government. Having been active in performing combat data collection and analysis during Operation Allied Force, he now leads the Joint Service Air Defense Lethality Team, coordinating efforts with the Army to perform combat data collection for Operation Enduring Freedom.

Mr. John M. Vice is President of Skyward, Ltd., a small business located in Dayton, Ohio. He has a B.S. in Aeronautical Engineering from the University of Wyoming and a M.S. in Aerospace-Mechanical Engineering from the Air Force Institute of Technology. Mr. Vice has many years experience in weapon system survivability with a special emphasis on aircraft battle damage repair and analysis of weapon system combat data. He worked to collect and preserve weapon system survivability data from combat experiences such as Operation Just Cause in Panama and Operation Desert Storm.

Mr. Donald Voyls has over 40 years of professional experience encompassing aircraft survivability, battle damage repair, and combat damage and loss data collection. He worked in the field to collect combat data during the Southeast Asia conflict and Operation Desert Storm and participated in the training of data collection teams. Mr. Voyls is currently technical advisor to the 46th OG Survivability and Safety Flight and the Air Force Research Laboratory on data collection and aircraft battle damage repair. He has a B.S. degree in Aeronautical Engineering.

In Shah-E-Kot, Apaches Save The Day—And Their Reputation

by Mr. Sean D. Naylor, Army Times staff writer
Reprinted with Permission from the Army Times, March 25, 2002, Page 15

Editor's Note: *The JTCG/AS and two of its charter members, Roland Bernier and Don Mowrer from the U.S. Army Ballistics Research Laboratory (now Army Research Laboratory), contributed to the battlefield success of the Apache Helicopter. Roland and Don capitalized on lessons learned in Southeast Asia and the latest JTCG/AS vulnerability reduction technology to establish ballistic vulnerability specifications that were then implemented as the helicopter was being developed. As a result, the AH–64 was one of the first helicopters to have vulnerability reduction built-in from the very beginning of the design process. The survivability of our aircraft and warfighters in combat has been the goal of the JTCG/AS since its inception and it is rewarding to see that it paid off in saving aircraft and lives in combat.*

The soldier's weather-beaten face was streaked with tears of gratitude. Just days earlier, separated from his buddies and pinned down by intense fire from Al-Qaida soldiers in the ridgelines around the Shah-e-Kot valley, he thought he was going to die. Then, like fire-spitting avenging angels, Apache attack helicopters sliced through the thin mountain air pouring rocket and chain-gun fire on his would-be killers.

"We came in and took the fire away from him," said Capt. Bill Ryan, the commander of those Apaches. He said it matter-of-factly, as if there were nothing remarkable about piloting a helicopter through hails of bullets and rocket-propelled grenades to save a man's life. Now safely back at Bagram Air Base, that soldier had come to thank his deliverers. As Operation Anaconda wound down, a string of well-wishers stopped by to pay homage to the dozen or so Apache pilots who had kept the al-Qaida troops at bay.

Not every visitor broke into tears. But all echoed the sentiments of Lt. Col. "Chip" Preysler, commander of 2nd Battalion, 187th Infantry Regiment. Preysler's battalion was one of two that flew into the teeth of entrenched al-Qaida positions March 2, the first day of the operation. Their very lives depended on Ryan's seven Apaches for close air support. When he came out of the battle nine days later, Preysler immediately sought out Ryan. With a smile on his face and his hands spread wide, he said, "You guys have huge balls."

The Apache exploits on the first day of the battle of Shah-e-Kot have done much to bolster the reputation of an aircraft that saw its battlefield role called into question after its role in Albania in 1999. In that bleak period in the helicopter's history, 24 Apaches were sent to Task Force Hawk for use in the war against Yugoslavia. But the choppers were held back

from combat after two crashed and two pilots died during mission rehearsals. The Apache community complained that ignorant journalists and casualty-averse Pentagon officials had unfairly turned their beloved killing machine into a scapegoat.

Now, three years later, the contrast could not be starker. The Apache drivers are being lauded as heroes, and their helicopter is receiving what to many pilots is praise long overdue. With al-Qaida fighters so close to U.S. troops that close air support from "fast mover" jets was often out of the question, the Apaches became the only fire support available to ground commanders. In the crucial hours of that first day, when the carefully scripted battle plans had been rendered irrelevant and the outcome hung in the balance, Apaches saved the day.

"The weapon that changed the face of the battle for us was the Apache," said Col. Frank Wiercinski, commander of the 101st Airborne Division (Air Assault)'s 3rd Brigade and in charge of all conventional U.S. troops in the battle. "I was just so impressed by its capability," he said. "I had never seen the Apache in combat before, though I've always trained with it. I am a firm believer right now that a brigade combat team commander needs his Apache battalion in an air assault division—its ability to protect us en route, its ability to set the conditions on the landing zones and then its close combat attack capability to take out fires.

"Artillery is a wonderful asset, but you need an observer, you need a sensor, and then you've got the artillery [tube] as the shooter. An Apache can do all of that, and it's always moving." On station in the valley from dawn on the battle's first day, the Apaches flew again and again through withering small arms, heavy machine-gun, and rocket-propelled grenade fire to provide fire support to the beleaguered infantry troops.

Five Apaches were present at the start of the battle, a sixth arrived later that morning and a seventh flew up from Kandahar to join the fight that afternoon. None of the helicopters was shot down, but four were so badly damaged they were knocked out of the fight. The fire the Apaches braved was so intense that when the day was over, 27 of the 28 rotor blades among the seven helicopters sported bullet holes, said Lt. Col. James M. Marye, the commander of the 7th Battalion, 101st Aviation Regiment. Marye's aviation task force included the Apaches of Ryan's A Company, 3rd Battalion, 101st Aviation. Beneath the cold numbers are tales of heroism and extraordinary achievement. None are more dramatic than the story of Chief Warrant Officer 4 Jim Hardy.

This photo is of an AH–64 helicopter that was shot during combat in Afghanistan.

At about 6:45 a.m., an RPG exploded under the nose of Hardy's Apache, sending shrapnel slicing through the helicopter's innards. "I looked up and there was a black puff of smoke, like World War II flak," said Chief Warrant Officer 2 John Hamilton, who was flying nearby. "There was major damage to that aircraft," Ryan said. "They had lost the weapons systems and the target-acquisition systems." Despite the fact that Hardy's Apache was now essentially unarmed, he stayed on station. He later told Hamilton that his plan was to fly up the valley and draw fire, allowing the other Apaches to engage enemy gunners once they had revealed themselves.

About 10 minutes after an RPG struck Hardy's aircraft, another hit the Apache piloted by Chief Warrant Officer 3 Keith Hurley, smashing into the left Hellfire missile launcher. "The RPG struck me on the left, rocked the aircraft, and a microsecond after that, a bullet came through the cockpit," Hurley said. By the end of the day there were 13 bullet holes in Hurley's aircraft. Lights immediately started flashing on Hurley's control panel, warning him that he was hemorrhaging oil. Hardy, one of the

company's most experienced pilots, realized Hurley was in trouble, and got on the radio. As Hurley recalls it, Hardy told him, "I've got to go back to the [Forward Arming and Refueling Point], fall in trail and follow me, and we've got to go quick."

The two wounded Apaches headed for the FARP, a way station for the helicopters roughly halfway between the valley and their temporary base in Bagram, north of Kabul. They didn't make it very far. About a mile west of "the Whale," the humpbacked ridgeline that marked the western edge of the valley, more lights came on in Hurley's cockpit, including one that told him he had no fluid left in his transmission. "I called off the lights to Mr. Hardy and he said, 'You've got to land, you've got to land now,'" Hurley said. The two landed in a dried-up riverbed, within range of the al-Qaida positions. With bullets flying around him, Hardy, who Hurley described as "the unit maintenance god," shut the helicopters down and went to work on Hurley's aircraft. "He did sort of a triage of the aircraft, examining it like a doctor," Hurley said. Hardy took the three one-quart oil cans that each helicopter carried as spares and poured all six quarts into Hurley's engine. Then he told Hurley they were going to swap helicopters and fly back to the FARP. "He told me, 'Don't dick around, when I get it started, I'm going,' " Hurley said. Hardy was drawing on his deep knowledge of the Apache to take a calculated risk.

With Hurley's chopper leaking fluid like a sieve, he knew the six quarts of oil he had just poured in would not last long. But he also knew that the Apache's engine was supposed to last 30 minutes without oil before seizing up. Hardy was gambling that he could nurse Hurley's Apache 50 miles to the FARP in less than half an hour. The alternative was to strap two of the four pilots onto the side of Hardy's helicopter, leaving Hurley's Apache behind as a dead loss.

Hardy's gamble paid off. Twenty-six minutes after taking off under fire from the riverbed, the two damaged Apaches landed safely at the FARP. Hardy's colleagues were in awe. "There are not a lot of folks out there who would have taken that aircraft off the ground," Ryan said. "It was an incredible action by Mr. Hardy."

Hamilton said: "He's a hero, no doubt about it." Marye recommended Hardy for a Distinguished Flying Cross. He also recommended Ryan, who continued flying despite being nicked on the chin by a bullet, for a Silver Star and several other pilots for the Air Medal with "V" device. ◆

Yellow smoke blows from a smoke grenade marking the position of 2nd Battalion 502nd Infrantry Regiment for AH–64 Apache helicopters to see at Ramnjane range in Ramjane, Kosovo on 19 September, 2001.

Photo by SFC Martin J. Cervantez

Modeling the Anti-Helicopter Mine Threat

by Mr. Sean Townsend and Mr. Kirk Wright

JTCG/AS Sponsored Project

One of the primary advantages of helicopters is their ability to perform low-altitude, nap-of-the-earth flight. This allows them to avoid radar and visual detection and accomplish mission objectives impossible for other aircraft. However, this also puts them at risk to a new threat, the anti-helicopter mine (AHM). These mines use acoustic, infrared (IR), and radio frequency (RF) sensors to detect, identify, and locate helicopters. When the helicopter comes within range, a warhead is triggered to destroy the helicopter.

Fortunately, no U.S. aircraft has yet faced an AHM in combat. Due to the relatively recent development of this threat, a window now exists for countermeasure development to protect our flight personnel. For this reason, the JTCG/AS and PM Aviation Electronic Systems have funded Dynetics, Inc. and the U.S. Army Aviation and Missile Command to develop the Generic Reconfigurable Anti-Helicopter Mine Model (GRAHMM). The generic sensor and warhead modules provided in GRAHMM facilitate analysis of the AHM threat and a means to evaluate the performance of potential countermeasures.

Threat Status

The Worldwide Equipment Guide published by TRADOC DCSINT Threat Support Directorate lists four countries with mines either in production or development—being Bulgaria, Austria, Russia, and the UK. The Bulgarian version uses RF and acoustic sensors while the other three versions use acoustic and IR sensors. A sample of an AHM is shown in Figure 1.

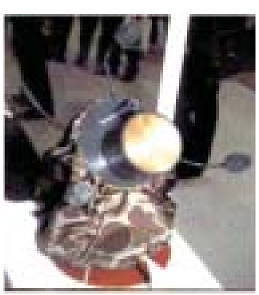

Figure 1. A Russian AHM that is available on the open market.

The danger posed by AHMs is increased because of their operational characteristics. As with traditional land mines AHMs are low cost weapons with low-power consumption that allow extended periods of unattended operation. Their low cost also means that they could be deployed in large numbers to protect key assets and likely helicopter entrance routes such as mountain passes. Sea-based derivatives of current AHMs could also be developed to detect and destroy helicopters used to sweep for anti-ship mines.

AHMs typically use an "always-on" acoustic sensor for initial target detection. After detection the acoustic signature is analyzed to determine if it is from a helicopter. In the more sophisticated mines logic may be present to determine the helicopter type from the received signature. Once the acoustic sensor has detected a potential target it activates one or more secondary sensors. The secondary sensor acts as a fuze with the field of view and detection range matched to the warhead characteristics. When the secondary sensor detects the target within the lethal area of the warhead, the mine is detonated. The warhead is usually a fragmentation, multiple explosively formed penetrators, or a combination that provides a lethal range of approximately one to two hundred meters.

Model Description

For maximum re-use GRAHMM has been developed using the Joint Modeling and Simulation System (JMASS) architecture. Each portion of the mine is modeled as a separate "player" allowing the user to easily reconfigure a mine with any combination of sensors and warheads. Acoustic, RF, and IR sensor players are available. Each has configurable parameters to control update rate, sensitivity, processing logic, and sequencing. In addition, the warhead model represents the spectrum of possible AHM munitions.

A significant portion of the project has been the development of acoustic and vulnerability "environments" within JMASS. While the RF and IR sensors were able to use existing environments to model effects such as signal propagation loss between the target and the sensor, no such environment existed for acoustic propagation. After investigating a number of acoustic propagation models, the Fast Field Program (provided by ARL) was selected to compute the acoustic propagation loss. Inputs needed

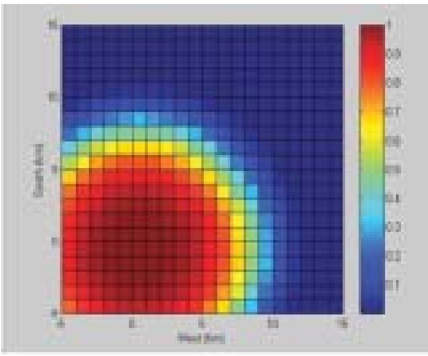

Figure 2. A probability of detection map generated using a nominal acoustic sensor against a threat representative helicopter in GRAHMM.

for the acoustic propagation include atmospheric temperature and wind profiles as well as ground surface properties. Figure 2 shows an example of a probability of detection map generated for a nominal acoustic sensor against a threat representative target. The vulnerability environment is used to assess the warhead/target interaction and provide susceptibility and vulnerability information. Susceptibility data is provided in the form of hitpoints and points of closest approach, with respect to a 3D model of the target. This data can be easily viewed in the context of the target geometry using FacetManip, a data visualization tool and input generation utility that has been developed for use with the model. Figure 3 shows FacetManip being used to display hitpoints.

Vulnerability capabilities are provided in two forms. If sufficient target and scenario data are available to define an AJEM (Advanced Joint Effectiveness Model) run, the AHM model provides the required munition projectile information (position, velocity, mass) to AJEM. AJEM can then be used to determine user specified vulnerability measures that incorporate, hit location, blast effects, aircraft redundancies, internal structure, hit densities, etc.

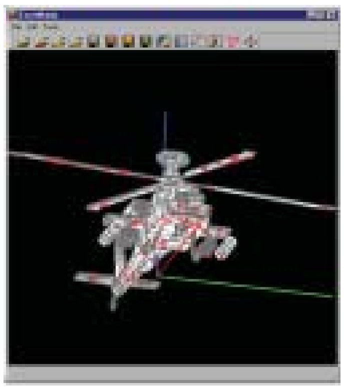

Figure 3. Visualizing hitpoint distributions generated by GRAHMM by using FacetManip.

Unfortunately, to achieve this level of fidelity, large amounts of data are needed but may not be available. If the use of AJEM is not feasible, an integrated, simple, lower fidelity graphical vulnerability module (GVM) has been developed that resides within the vulnerability environment. GVM uses known vulnerability information (e.g., probability-of-kill maps as a function of aspect angle) to perform table lookup interpolation within the vulnerability environment.

Project Status

We are just completing the second year of the project, which concludes the generic model development. The current model consists of all the key elements needed to model the known threats and during the third year the model will be configured to represent the specific attributes of these threats. Output of the model will be used with U.S. aircraft signature and vulnerability data to assess the threat posed by these mines. Whenever possible the model results will be compared with known test results. If warranted, after assessing the threat, we will begin to analyze potential countermeasure ideas so that our aircraft are able to accomplish mission objectives unhampered by AHMs. ◆

Mr. Sean Townsend received his Master's degree in Mathematics from the University of Kentucky in Lexington, Kentucky. He received a B.S.in Mathematics from Butler University in Indianapolis, Indiana. Sean is a Systems Analyst with 5 years of experience at Dynetics, Inc. in Huntsville, Alabama. He works mainly in vulnerability visualization and the development of IR sensor models. He may be reached at sean.townsend @dynetics.com.

Mr. Kirk Wright is currently the Team Leader for the Apache Longbow Computer Resource Management Team (CRMT) in the U.S. Army PEO for Aviation. Kirk has served as Team leader for the ATIRCM/CMWS CRMT, also in PEO Aviation, and has 16 years of experience in the development and sustainment of airborne weapon systems including USAF systems. Kirk received his M.S. in Computers and Information Systems from Mercer University, Macon, Georgia, and B.S. in Electrical Engineering from Mississippi State University.

Army Aviation Battlespace—Working the Survivability Challenge

by Mr. Wesley F. McElveen

The Escalating Threat

The overarching goal of the Army's transformation initiative is full spectrum dominance for the Objective Force.[1] The transformed Army will be significantly more agile, responsive, versatile, lethal, deployable, sustainable, and survivable—battlespace notwithstanding. Battlespace for legacy, interim, and Objective Force air warriors and their rotary-wing platforms is by doctrine "the low altitude, nap-of-the-earth" domain. This places Army aviators in a particularly robust and intensely challenging threat environment. The challenge is directly traceable to an equally robust variety of highly mobile, extremely accurate, surprisingly affordable Surface-to-Air Missiles (SAMs)—including Man-portable Air Defense Systems (MANPADS) and radar controlled Anti-Aircraft Artillery (AAA) guns. Former Soviet Union (FSU) SAMs alone are deployed in over 80 countries;[2] and inventories in some contain more than 25 different types of SAMs and AAA weapons. China has 30 and Russia 34, for example.[3] Ten to twenty is typical. At least 18 countries are currently producing MANPADS,[4] many of which are available for legitimate export. Global black-market sales are also strong. In fact, the belief is that over 20 terrorist groups operating in multiple countries through international networks now have access to MANPADS.[5] Afghan rebels repeatedly demonstrated the effectiveness of heat-seeking MANPADS during the Soviet-Afghan war. Using Stingers supplied by the U.S., Mujahideen rebels achieved a 79 percent success rate, scoring 269 aircraft kills out of 340 heat-seeking Stingers fired,[6,17] effectively driving Russian aircraft from the skies of Afghanistan.

Heat-seeking missiles destroyed at least 20 U.S. Aircraft during Desert Storm.[7] Moreover, an analysis of worldwide aircraft losses over a 15-year timeframe confirmed that 80 percent were traceable to heat-seeking missiles.[8] Consider the observations of Major Kevin Iiams, USMC tactical pilot and SAM-attack survivor with 41 combat missions: "…I have changed my view over the years of the EO/IR SAM, from seeing it as a planning nuisance to seeing it as a formidable…threat. …Without a doubt the EO/IR SAM is an extremely potent weapon system."[9] Other been-there-and-done-that aviators and combat veterans have similar views."Our strike planners worry about…man-portable SAMS…because we've learned the lesson of those who went before and of our own experiences…." (Lt Gen George S. Newbold USMC).[10] "The reality today seems to be that…we are electing to relinquish day-time battlespace below 15,000 feet to any enemy possessing a significant number of MANPADS and rapid fire AAA weapons" [Rear Admiral, Robert H. Gormley, U.S. Navy (ret.)].[11]

Leading edge MANPADS, such as the French Mistral and the UK's Starstreak, can present a special set of challenges—given their availability for export and possible theft by terrorist groups. The Mistral has built-in decoy avoidance capability and there is no known operationally deployed countermeasure for the Starstreak. Since 1990, thirty-six different armed forces deployed in (at least) 24 countries have ordered more than 15,000 Mistral missiles.[12] MANPAD versions of Starstreak are not yet exportable, however, other configurations apparently are.[13] Both Mistral and Starstreak are said to be extremely effective. Anecdotal evidence suggests Starstreak may well have a 0.96 single shot kill probability.[14]

Cheaper, more mobile, and capable of greater ranges than AAA gun systems, MANPADS' affordability and demonstrated effectiveness reportedly have increased sales significantly in the international market place. This may be especially true for economically depressed countries and non-state sponsored groups, such as terrorist organizations.[15] Often valued at no more that $20,000 to $70,000 per system, the worldwide MANPADS inventory now exceeds 500,000 missiles.[16]

Without effective self protection for Army aircraft, global proliferation of MANPADS clearly represents a

serious survivability challenge for Army aviation and boldly removes critically important opportunities for battlespace dominance. The likelihood of a helicopter being destroyed by SAMs is three times that of a transport aircraft and two times that recorded for fighter bombers.[17] Bottom line—

1. Low altitude airspace in many scenarios is dominated by MANPADS, and
2. Superior self protection for Army aircraft is a survivability imperative.

Addressing the Threat

The Army's response to its growing aircraft survivability imperative is the Suite of Integrated Infrared Countermeasures (SIIRCM), and the Suite of Integrated Radio Frequency Countermeasures (SIRFC). The SIIRCM and SIRFC provide leading-edge protection against IR and RF threats respectively. Both systems are also modularized and reconfigurable. The SIIRCM configurations have been 100 percent effective in live fire tests against actual threat missiles in the IR spectrum. Key SIIRCM subsystems include the

1. Infrared Jam Laser,
2. Infrared Jam Head,
3. Jam Head Control,
4. Electronic Control Unit,
5. Missile Sensors, and
6. Improved Countermeasures Dispensers and Sequencer.

Configurations with less capability but significant cost reductions are available and currently also being considered as procurement options. Unit cost is profoundly impacted by procurement quantities. For example, procurement quantities of sufficient magnitude to support a production rate of eight SIIRCM systems per month would reduce the cost per system over 40 per-

Figure 1. AH–64A APACHE with Ordnance.

Figure 2. Suite of Integrated IR Counter-measures (SIIRCM).

cent, when compared to a baseline production rate of four units per month.[18] Results from another interesting simulation analysis, based upon an approved operational scenario, suggest that an Apache attack battalion equipped with SIIRCM and deployed in a high threat environment could save up to 18 lives and $162M after only four missions.[19]

With respect to threats functionally active in the radio frequency spectrum, SIRFC configurations provide both RF warning and RF countermeasures support. The system provides for

1. Situation awareness,
2. Sensor fusion,
3. Resource management,
4. Target identification, location and cueing,
5. Electronic countermeasures against a robust spectrum of radars and missiles.

The SIRFC product family has sufficient built-in flexibility to accommodate extensive requirement-based tailoring. Five operationally viable configurations are available,[20] beginning with the standard radar warning receiver and continuing through to a fully integrated electronic warfare suite. Each of the five configuration options currently is being considered for production and fielding. Final selections will be based on specific warfighter needs and budget constraints. The cost delta between the base configuration (option #1) and a fully mature SIRFC (option #5) exceeds $1M per system.[21] The range of cost-performance trade options makes the SIIRCM and SIRFC systems more affordable when configurations are tailored to meet specific aircraft mission needs.

Full spectrum dominance for the objective force begins with survival. Helicopter Survival

in the low altitude battlespace will be significantly enhanced by the SIIRCM and SIRFC. Both SIIRCM and SIRFC programs are supervized by the Aviation Electronic Systems Project Officer located at Redstone Arsenal, Alabama. Management oversight and executive leadership is provided by the Program Executive Officer for Intelligence, Electronic Warfare and Sensors located at Ft. Monmouth, New Jersey. ◆

Author's Note: *I am indeed grateful for the research assistance and helpful suggestions provided by Mr. Henry Flick. I am equally grateful for the much-needed secretarial and administrative support given by Mrs. Teressa Hendrix. Without their help, I would not have been able to complete the manuscript for this article.*

Mr. McElveen assumed duties as Project Manager for Aviation Electronic Systems, Program Executive Office, Intelligence, Electronic Warfare and Sensors, Huntsville, Alabama, in 2001. Mr. McElveen has over 40 years of Federal service, 30 being accumulated while on active duty with the U.S. Army. Following Military duty, Mr. McElveen was employed by the U.S. Army Metrology and Calibration Center where he worked in various science and engineering positions until 1989 when he accepted a cost analyst position with the Strategic Defense Command. His awards include the Legion of Merit, Defense Meritorious Service Medal, Meritorious Service Medal (two awards), Army Commendation Medal (three awards) and the Superior Civilian Service Award. He holds a Master's Degree in Computer Science and Technology from Alabama A&M University and a Bachelor's Degree in Mathematics from William Carey College, Hattiesburg, Minnesota.

Photo by SFC Martin J. Cervantez

Figure 3. A UH–60 Blackhawk helicopter takes off for an air assault exercise.

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Exploring Better Ways To Determine In-Flight Wing Damage

Dynamic Loading Methodologies

by Dr. Monty A. Moshier, Ph.D., Dr. Ronald L. Hinrichsen, Ph.D., and Mr. Gregory J. Czarnecki

It's becoming clear that current static loading techniques for live-fire testing fail to accurately replicate the loads of aircraft that are damaged in flight. Unfortunately, vulnerability assessments based on such loading techniques may also, in turn, fall short of providing accurate and complete results. The good news is advances in a proposed technique for dynamic live-fire ground testing may remedy the shortcomings of current static ground testing. And in response, the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) is funding the Dynamic Loading Methodologies (DLM) program.

One aspect of the DLM program includes developing an exciting new strategy for more accurately testing in-flight damage to aircraft. In this article, we'll explore this promising new approach. But let's first identify the main shortfalls with static ground testing.

When a wing is damaged, its dynamic response is primarily from the reduced stiffness of the wing and the wing's loss of resistance to flutter, (or reduced flutter speed). A damaged wing can survive and the aircraft continue to fly if—

- Static stiffness is sufficient to withstand the aerodynamic loads (this assumes that sufficient lifting capability remains)
- Damage does not reduce the flutter speed such that the wing responds in a manner that it uncontrollably flutters and destroys itself.

In live-fire testing of aircraft wings, quasi-static ground loading techniques do not account for changes in structural stiffness and mass that occur from damage. As such, current loading methodologies fail to reconfigure correctly for representing in-flight loads. Ground loading methodologies also fail to consider damage-induced changes to the flutter envelope that can lead to premature failure.

What's needed is a different reconfigurable ground loading methodology that conforms to a wing's change in stiffness. And this must be combined with an analytical procedure that considers a wing's damage state and predicts a revised flutter envelope. Such a new ground loading procedure and complimentary flutter analysis will support live-fire testing and assist in generating reliable and complete test assessments and vulnerability analyses.

Defining a New Approach

Modeling and simulation, using a representative fighter aircraft model, helped us develop a new reconfigurable ground loading methodology to better predict the time response of an in-flight aircraft wing to damage. Our approach included—

- Obtain a validated finite element structural model and couple it with an aerodynamic flow model.
- Perform a time integrated finite element simulation of an in-flight aircraft. During the simulation, at $(t = 0)$ apply the g-loading and aerodynamic loading to the model.
- Allow the model to come to a steady state condition.
- At a time when the model is at or near steady state $(t = t_1)$ instantaneously inflict damage (equivalent to a specific threat) by removing structural elements from the model.
- Monitor the time history of displacements and strains at specific points in the model.
- Design a ground loading system to mimic the model response for the 1–2 seconds following the damage.

We obtained a finite element structural model of a representative fighter aircraft in NASTRAN format. This model had been previously validated for use in dynamic analysis and optimization. The NASTRAN model was translated into the LSDYNA3D format using a combination of MSC/PATRAN, FEMB , and user written translation codes. The resulting finite

element model—consisting of 4,226 nodes, 2,016 beam elements, 4,984 shell elements, and 998 lumped masses and inertias—appears in Figure 1.

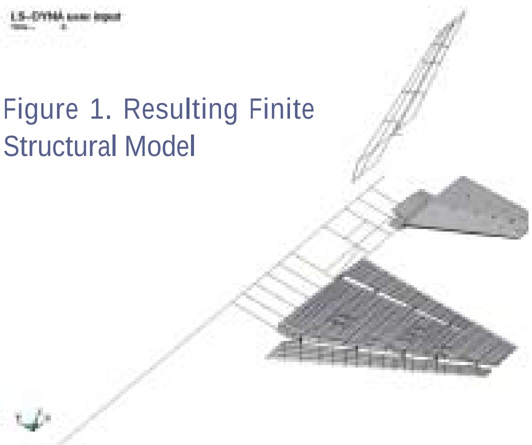

Figure 1. Resulting Finite Structural Model

Because the focus of this work is on the wing, the highest fidelity elements were used there while other structures were modeled with less fidelity. The fuselage, vertical, and horizontal tails are essentially beam models.

The aerodynamic paneling model used was a boundary element method based on the VSAERO code and appears in Figure 2.

Because the model is based on linear aerodynamic theory, it's applicable for inviscid, incompressible fluid flows. It consists of 336 elements using nodes that are coincident with and numbered the same as the structural model nodes. By imposing the coincidence of the aero and structural nodes, pressures generated by the aero model are directly applied to the structural nodes.

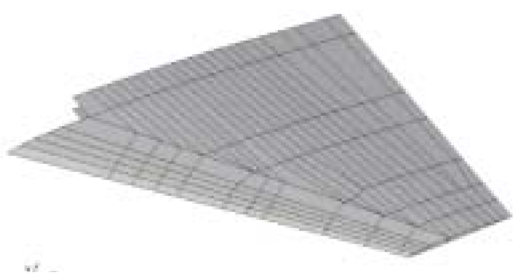

Figure 2. Aero-Dynamic Panel Model

The coupled aero/structural model assumes symmetry about the centerline of the aircraft with the structure fixed at the center of mass of the symmetric model.

Revalidating the Model

After the NASTRAN finite element model of the structure was converted to LSDYNA3D format, we needed to revalidate the new model. We achieved this by comparing the performance of the two models against existing data that had been obtained from earlier static and dynamic ground tests.

- **Static validation**—The new LSDYNA3D model displacement was quite sensitive to the imposition of the cantilevered boundary condition. When compared to the original NASTRAN model, the LSDYNA3D was significantly better, depicting a displacement about 5 percent greater than ground test.
- **Dynamic validation**—Due to the explicit nature of the LSDYNA3D code, natural frequencies were determined in the time domain by cantilevering the wing model at the root and "plucking" the wing tip. The time history of displacement in the z direction of selected nodes was extracted and a fast fourier transform (FFT) was applied to obtain the frequency response. The difference between the LSDYNA3D model and the ground test values varied between 6% and 16%.

Using this validated, coupled aerodynamic/structural finite element model, let's now explore the results of three sample simulations.

Simulating Dynamic Response to In-Flight Damage

The results we'll discuss are from simulations in which the wing was undamaged for the first 10 seconds with instantaneous damage to the wing occurring at t=10 seconds followed by an additional 10 seconds of simulation.

The aerodynamic paneling method used in LSDYNA3D does not currently allow for ramping up of the aerodynamic flow. Because of this, the initial 10 seconds of simulation is required, allowing the wing's response to the step loading from the aerodynamic flow to reach a steady state. Instantaneous damage to the wing at t=10 seconds is achieved by removing elements associated with the assumed damage. The resulting dynamic response from the damage and applied aerodynamic loading is then captured in the final 10 seconds of the simulation. The aerodynamic mesh does not change throughout the simulation.

Sample Case 1—Clean Wing Damaged (Moderate) Near The Wing Root

The model simulation was for the aircraft at an angle of attack of 6 degrees, altitude below 4,000 feet and mach 0.8 (see Figure 3).

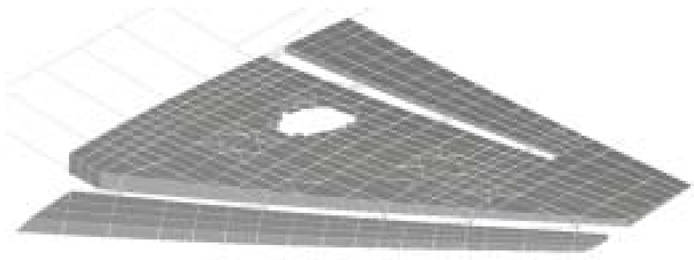

Figure 3. Sample Case 1. Typical Damage – Mach 0.80

This case illustrates this particular wing's structural redundancy. After the wing reaches steady state, aerodynamic loading causes the undamaged wing to deflect approximately 3.5 inches, as measured from B.L. 120 (see Figure 4).

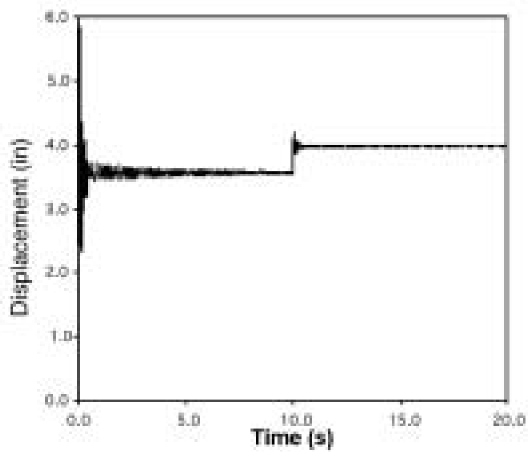

Figure 4. Deflection At B.L. 120 For a Clean Wing and Typical Damage – Mach 0.80

The above chart also shows that once damage occurs, the instantaneous loss of structural stiffness initiates some brief oscillations followed by a steady state deflection that is approximately 0.5 inches more than the pre-damage state.

Under these simulated flight conditions, the wing's reduction of stiffness due to damage doesn't affect the dynamic response of the wing sufficiently to cause catastrophic failure. However, brief oscillations experienced immediately following damage, under the right conditions, may cause additional damage that results in additional stiffness loss that may propagate.

Let's take a look at this wing's redundancy by examining stresses in the damaged spar caps. As shown in Figure 5, spar cap stresses exist in spar caps 6 and 7 before and after damage.

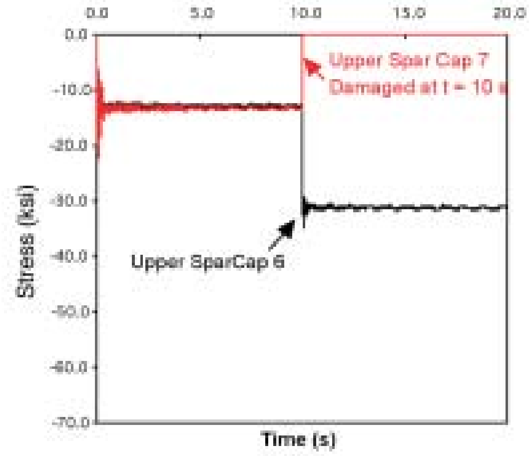

Figure 5. Spar Cap Stresses Before and After Damage

Portions of spar cap 7, 8, 9, and 10 are eliminated at time t=10 seconds. Before damage is input, spar caps 6 and 7 are loaded to about –12 ksi. After damage, spar cap 6 is loaded to –30 ksi because it carries additional load from the damaged spar caps. The yield stress of aluminum used in modeling the spar caps is 70 ksi. As can be seen, the post-damage stresses are far below the allowable yield.

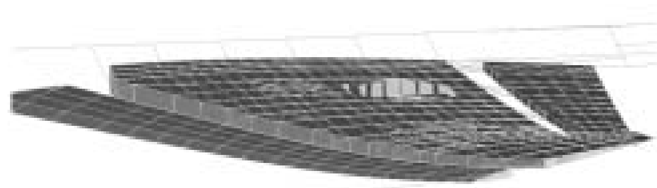

Figure 6. Sample Case 2. Typical Damage With Wing Tip Store – Mach=0.92

Sample Case 2—Clean Wing Damaged (Moderate) Near The Wing Root With A 300 Pound Store Attached To The Wing Tip

This model simulation was for the aircraft at an angle of attack of 3 degrees, altitude below 4,000 feet and mach 0.92. The 300 pound store was modeled as a series of simple beams.

This case (see Figure 7) illustrates the wing's deflection and tortuous shape caused by the damage and reduced flutter resistance.

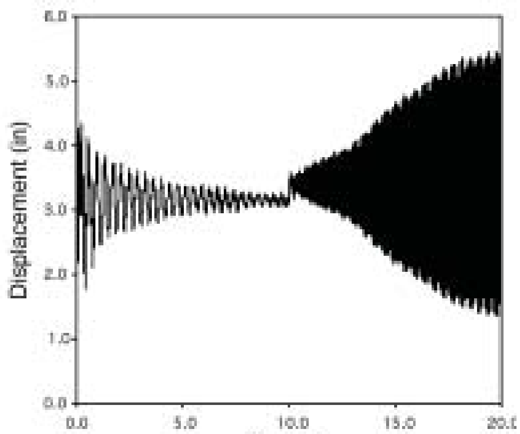

Figure 7. Deflection At B.L. 120 For Wing + 300 lb Store and Typical Damage – Mach = 0.9

In this case, the oscillations associated with step loading the wing at the beginning of the simulation require more time to reach steady state than the previous case.

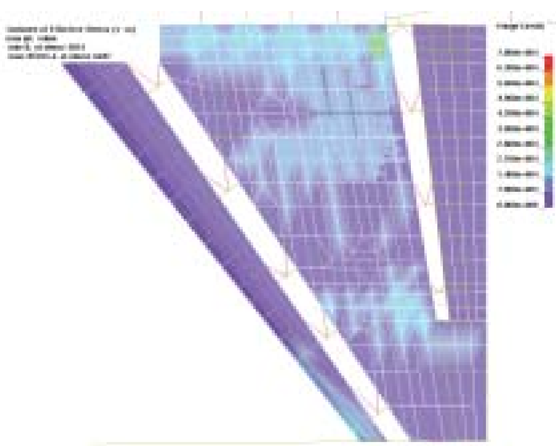

Figure 8. Von Mises Stress Contour Plot for Wing Before Damage.

After damage, the deflection diverges due to the lower stiffness and reduced flutter speed. The reduced flutter resistance caused by the damage led to increased deflections resulting in stresses that exceed the allowable yield stresses of the materials used.

You can compare the Von Mises stresses for this wing prior to damage and after damage in the following illustrations. In these illustrations the Von Mises stresses are scaled such that blue is 0 ksi and red 70 ksi, corresponding to the maximum allowable yield stress. Before damage the Von Mises stresses were all well below the yield stresses (see Figure 8) and after damage due to the increased deflections caused by flutter, the Von Mises stresses exceeded the allowable yield stress in the entire tip region (see Figure 9).

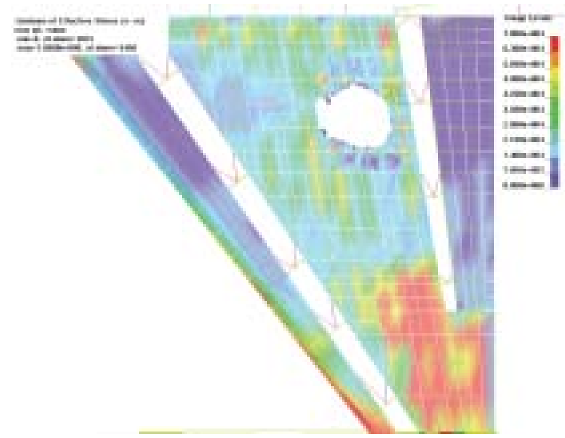

Figure 9. Sample Case 3. Typical Wing Tip Damage – Mach = 0.95

The likely result would be the loss of the wing tip and possible loss of the aircraft.

Sample Case 3—Dynamic Response Of A Clean Wing Damaged Near The Wing Tip

This model simulation was for the aircraft at an angle of attack of 3 degrees, altitude below 4,000 feet, and mach = 0.95 (see Figure 10).

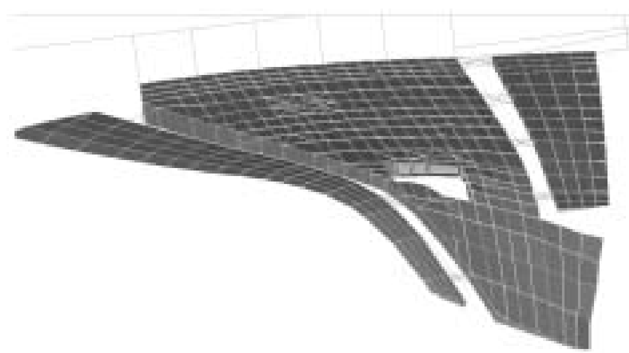

Figure 10. Sample Case 3. Typical Wing Tip Damage – Mach = 0.95

This case illustrates how damage causes severe wing distortion. After damage, the tip deflections have an oscillation of 50 inches (see Figure 11).

Before damage, the oscillations are a factor of 5 smaller. Note: the deflections presented are given at the

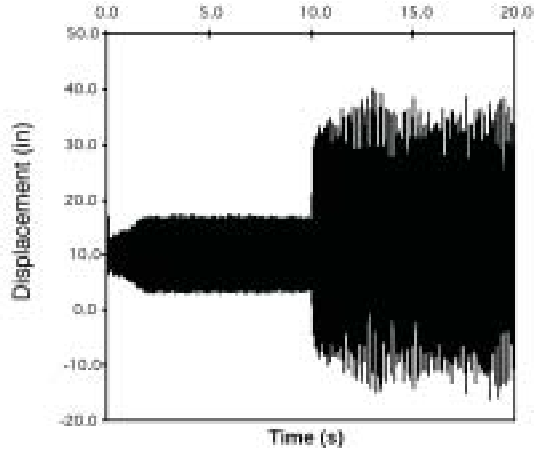

Figure 11. Deflection Of Wing Tip – Typical Damage Located Near Wing Tip – Mach = 0.95

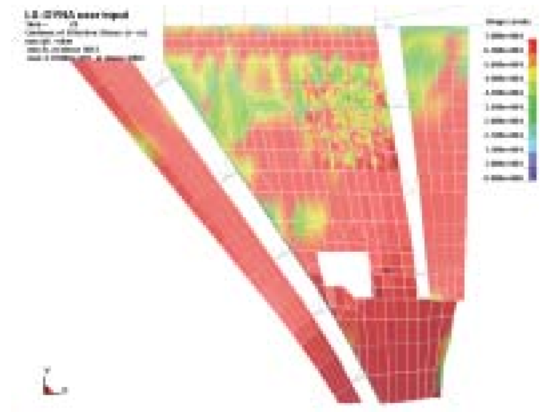

Figure 13. Von Mises Stress Contour Plot For Wing After Damage

wing tip and not at B.L. 120 as in the previous two cases. In this case, deflections at B.L. 120 were much less severe since the damage occurred outside of B.L. 120.

Now compare the Von Mises stresses for this wing before and after damage, respectively. Again, Von Mises stresses are scaled such that blue is 0 ksi and red is 70 ksi, with red corresponding to maximum allowable yield stress.

Before damage the Von Mises stresses are within the allowable range (see Figure 12) while stresses after damage are above the allowable for most of the wing (see Figure 13).

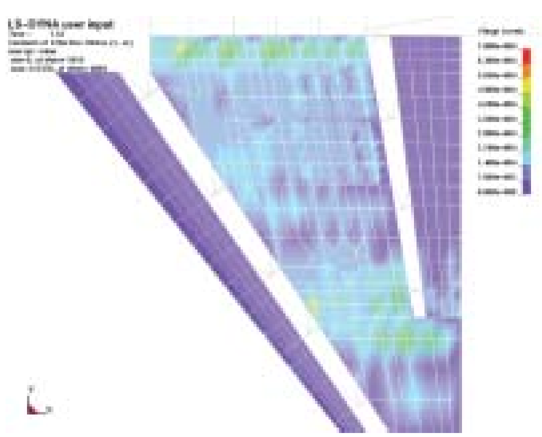

Figure 12. Von Mises Stress Contour Plot For Wing Before Damage

The obvious result from this simulation would be loss of the wing and aircraft, unless flight conditions were modified.

Planning Next Steps

Because of the nature and use of fighter aircraft, several different conditions, such as the effect of different stores, flight conditions, damage locations, and size, must be considered to better understand the wing's dynamic response when damaged. Beyond the three cases just shown, this DLM program investigated over 68 cases in which stores ranged from 200 to 2,000 pounds; flight conditions ranged from mach 0.8 to mach 0.95 below altitudes of 4,000 feet; and damage included three different damage sites and two different damage sizes.

We're pursuing the strategy discussed in this article to more faithfully represent the structural response of in-flight aircraft to damage. But we also understand the limitations of the aerodynamic model being used.

For example, the dominant source of damping in these simulations was due to the aerodynamics alone. No structural damping was added. Some numerical damping was present to ensure stability of the solutions, estimated to be less than 1% of that induced by the aerodynamics. No unsteady aerodynamics were modeled. The linear, incompressible, inviscid assumptions associated with the paneling method limit applicability of these analyses to subsonic conditions. Also, a linear material model was used for all materials.

Because of these limitations, Professor Charbel Farhat and his team at the University of Colorado are conducting an independent blind study. That team is using a Navier-Stokes CFD model for the aerodynamics. The goal is to quantify differences obtained by the two methods.

The intent is to use the fidelity of model appropriate for the flight condition of interest.

The team is investigating possible pneumatic, hydraulic, or combined loading techniques that could be used to apply dynamic loads during ground tests. It is anticipated that experimental ground testing can be applied for cases similar to case 1. The simulations have shown that the dynamic response and flutter resistance based on cases similar to that of case 2 and 3 results in deflections that if applied to an actual wing would lead to structural failure. Therefore, when flutter plays a key role in the dynamic response of the wing due to damage (cases 2 & 3), it's anticipated that computational analyses will be used as the primary tool for accurately assessing post-damage survivability.

As this article demonstrates, modeling plays a key role in determining appropriate loading methods for likelihood of aircraft survivability. But a full structural evaluation should account for more than just a maximum yield stress criterion as was done here. Many other failure mechanisms from plasticity to cracking must also be considered.

Planned future work in this promising area will yield additional results of dynamic analysis. These results, in turn, will help provide a pathway to test engineers for determining the most appropriate test method. That method could either be static, dynamic, or a combination of the two. And the good news there, is that subsequent concept designs of dynamic ground tests may then be based on improved predicted structural response. ◆

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Dr. Ronald Hinrichsen received his Ph.D. in Aeronautical Engineering from the Air Force Institute of Technology. He is currently a Senior Research Scientist at NCSA, University of Illinois. He may be reached at hinricrl@asc.hpc.mil.

Mr. Czarnecki received his B.S. in Civil Engineering and M.S. in Materials Engineering from the University of Dayton. He is a civilian with the 46th Test Wing's Aerospace Survivability and Safety Flight. Mr. Czarnecki is the Chairman of the Structures Committee under the JTCG/AS Vulnerability Reduction Subgroup. He may be reached at gregory.czarnecki@wpafb.af.mil.

Vulnerability Design Discipline

Photo by Staff SGT Shane Cuomo

by Mr. Hugh Griffis

JTCG/AS Sponsored Project

Acquisition reform, revolution of Modeling and Simulation (M&S), and Live Fire Test & Evaluation (LFT&E) legislation presents new opportunities and challenges. These events have forever changed the vulnerability design discipline.

Acquisition reform has changed the way design requirements are established. "How to" design requirements are gone forever. Vulnerability design requirements like "flight control systems shall be redundant and separated" are easy to understand but may result in sub-optimum, heavier, and costly design solutions. Today, performance-based requirements define required capabilities. A performance-based specification enables the weapon system contractor to select the "best" set of options to achieve the required performance. New weapon systems developments programs (e.g., JSF) are using performance based design requirements.

The weapon system program office's challenge is to define the appropriate, justifiable, and measurable performance-based requirements. The vulnerability discipline is well suited for this challenge because analytic tools are available to assess the vulnerability characteristics at a higher level of abstraction. Possible forms of ballistic vulnerability specifications are many. The concept of defining an "Engagement Probability of Kill" is attractive, as long as the engagement conditions are properly constrained to achieve the desired vulnerability characteristics. Definition of "Engagement Probability of Kill" as a vulnerability metric brings the disciple closer to warfighter's frame of reference. Ideally vulnerability specifications are related to the damaged vehicle's remaining military capability such as pilot ejection, retaining controlled flight until returning to friendly troops, and returning to base. This set of capabilities directly impacts the survival of the warfighter. "Pilot ejection over enemy forces" means the pilot may safely eject but may be captured by enemy troops. "Retaining controlled flight until returning to friendly troops" means the pilot ejects and goes home. While "pilot/air vehicle returns to base" implies the air vehicle requires battle damage repair. Linking remaining post engagement capability to the warfighter's operations provides a meaningful capability that alters the survival of the pilot, and potentially alters the outcome of the war.

Given performance-based requirements, weapon system designers have numerous available design options. Trade studies are completed to determine which potential solution can be implemented for the least weight and

Figure 1. (Above) An Air Force B1 crew chief, for the 405th Air Expeditionary Wing, prepares to launch a B–1B bomber on a combat mission, January 3, 2002, during Operation Enduring Freedom.

cost. These studies are coordinated across design disciplines to ensure the vulnerability reduction design solution does not adversely affect other design requirements. The impacts to other design disciplines are assessed for each potential vulnerability reduction solution. Typically, these trade studies require interaction across several design disciplines.

Modeling & Simulation (M&S) results are used to justify and optimize vulnerability reduction design solutions. M&S is used to generate numerical values (vulnerable area or engagement PK) for each vulnerability reduction feature's weight. Numerical results can be used to compare the relative effectiveness of different classes of design solutions. From a performance-based specification perspective, the contractor can implement fire suppression or hydrodynamic ram vulnerability reduction features as long as the performance based design requirements are achieved. Vulnerability M&S enables the contractor to select the "best" solution.

M&S tools, such as Computation of Vulnerable Area and Repair Time (COVART), enable the JSF designers to determine what equipment can be struck by the threat and the extent of damage. These tools allow the Joint Strike Fighter (JSF), now the F–35, designer to assess the value of moving critical equipment behind other equipment or separating redundant equipment. The JSF designers are using M&S to determine the fire vulnerability of each fuel tank wall. Based upon the dry bay volume, the quantity of fire suppressant is determined and the resultant installed weight is known. By combining the fire suppression installed weight and the vulnerability to each tank wall, the JSF designer is able to determine the location of most effective (least weight and most vulnerability reduction) fire suppression. M&S tools provide the numerical data necessary to support design optimization decisions.

The ability to properly complete quality assessments is dependent upon our vulnerability M&S models, pedigree of supporting data (test, threat, and configuration), and the experience of the analysts conducting the assessment. Key areas of the vulnerability M&S process have significantly improved. Computer Aided Design (CAD) tools were not available during the design of many currently fielded aircraft. Building a computer math model

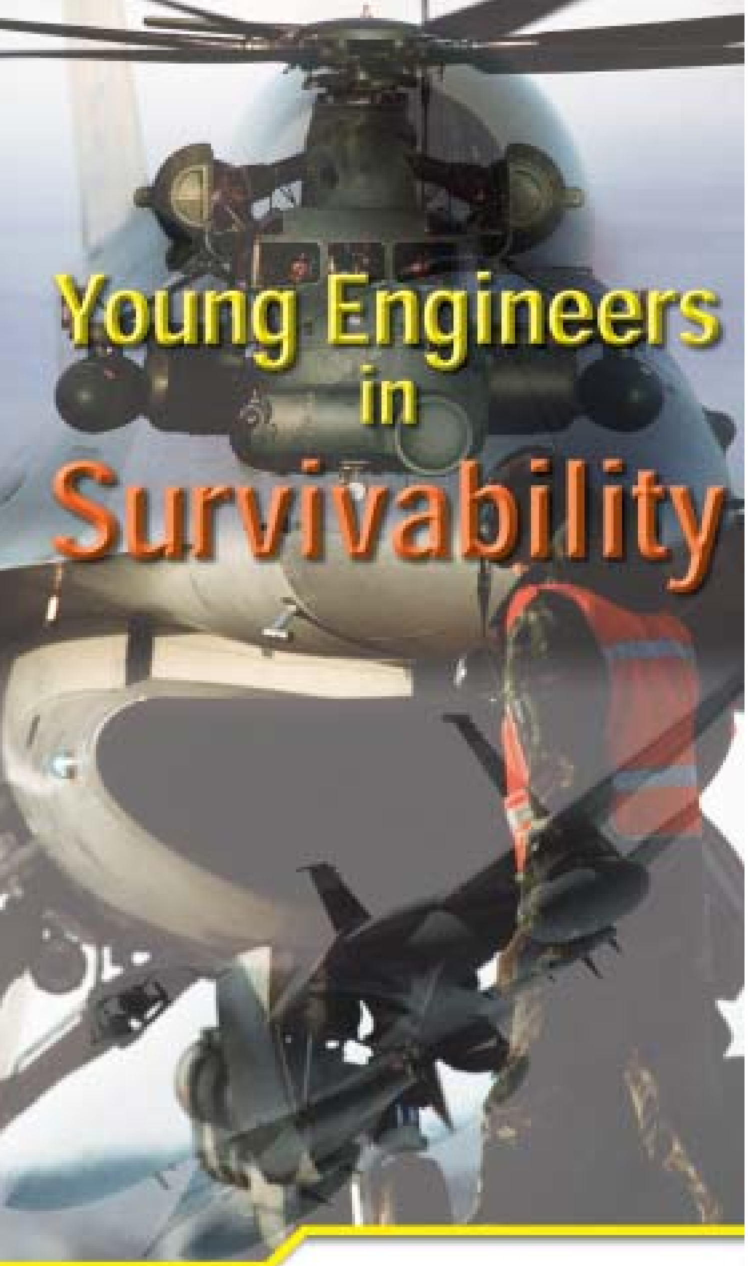
Figure 2. The Joint Strike Fighter (JSF) is an advanced tactical multirole aircraft developed for the U.S. Air Force, Navy, Marine Corps, and British Royal Navy.

of the air vehicle configuration (target geometric model) from drawings or technical orders is a daunting task. Target modeling for the JSF aircraft is based upon CAD databases. The JSF program has developed processes to significant reduce the effort of converting CAD databases into a FASTGEN target description. These processes allow the JSF analysts to generate high-quality target descriptions—faster, better, and cheaper. Even more important is that vulnerability assessment results are available soon after the configuration is updated, while the design is still in flux. During this short time-window, the cost of optimizing the design is relatively inexpensive.

Vulnerability M&S is not a pure science. Vulnerability M&S is a blend of empirically generated algorithms, engineering approximations, expert rules, and analyst-generated data. The accuracy of the M&S results at the system level is difficult to demonstrate. Over the years, LFT&E has generated data that enhances our understanding of air vehicles capability to withstand combat induced damage. LFT&E has also been used to generate data to calibrate specific portions of vulnerability M&S. The JSF program has leveraged F/A–18, F–22, and B–1 Joint Live Fire (JLF) and LFT&E results. These LFT&E results were used to build data to drive the JSF vulnerability assessment. This calibration process provides higher quality analyses therefore, reduces program risks of finding significant vulnerabilities late in the design process when design changes may be prohibitively expensive to correct.

Over the years, LFT&E has highlighted the M&S deficiencies in threat characterization data and damage mechanisms. LFT&E is a critical feedback loop to analysts and modelers. The usage of LFT&E results to calibrate M&S is critical to providing credible system level assessments. The concept of "Model-Test-Model" has been implemented within the vulnerability disciple and has provided a substantial return on investment. The JSF program has reaped huge benefits from prior LFT&E, prior model developments, and prior database developments. ◆

Mr. Griffis received his B.S. in System Engineering at Wright State University in 1981. He serves as the vulnerability/LFT&E technical advisor within the Engineering Directorate of the Aeronautical System Center at Wright Patterson AFB. Mr. Griffis system acquisition experience includes JSF, F–22, B–1, and B–2 aircraft. He has lead aircraft vulnerability reduction against ballistic, chemical, laser, and nuclear threats. He may be reached at 937.255.4358.

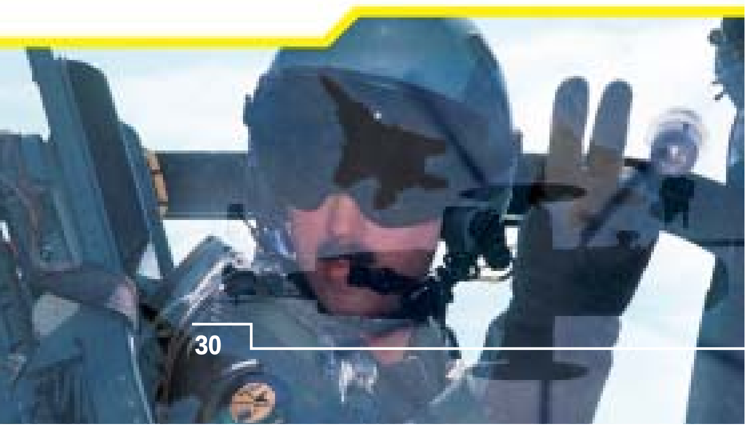


Young Engineers in Survivability

Joseph A. Manchor

Naval Air Warfare Center Weapons Division China Lake, California

by Mr. Dale B. Atkinson



The JTCG/AS is pleased to recognize Mr. Joseph Manchor as our first Young Engineer in Survivability. Joe is one of China Lake's bright young engineers who is doing an outstanding job in supporting the JTCG/AS, Joint Live Fire (JLF), Live Fire Test & Evaluation (LFT&E), and Navy fire suppression R&D programs.

Joe is a 1981 graduate of the United States Naval Academy at Annapolis, Maryland, and spent 11 years as a Naval Flight Officer on the world's premier Anti-Submarine Warfare (ASW) aircraft, the P–3 Orion. He also served during Desert Storm on-board the aircraft carrier USS Ranger, specializing in aircraft carrier defense and tactics. He served as a patrol plane tactical coordinator/mission commander, patrol plane tactical navigator, aircraft carrier tactical action officer, combat direction center weapons officer, and anti-submarine/anti-surface watch officer in his various assignments. Joe left active duty in 1992. He later joined the Naval Reserves, and was assigned to a Reserve UAV Unit where he received experience in UAV logistics and operations. This military experience has served him well because he is one of those people who can effectively apply his Military experience to his various programs to make them more realistic and practical with major payoffs to the warfighter.

After getting his Master of Science in Mechanical Engineering from Pennsylvania State University in 1994, Joe went to China Lake. His first job was as a project engineer in the Navy Energy Programs Office, where he did an engineering investigation and analysis to identify methods to reduce IR interference caused by photovoltaic solar panels located on Navy test ranges. Joe then moved to the Survivability Division where he has served as the Lead Engineer on a number of JTCG/AS, JLF, LFT&E, and Survivability R&D Programs since 1995.

His first job in the Survivability Division was as the Lead AV–8B Vulnerability Reduction Engineer, where he analyzed DESERT STORM AV–8B losses to identify vulnerabilities and recommend ballistic testing to confirm these vulnerabilities. He prepared test plans, conducted ballistic testing, reported on the results, and recommended vulnerability reduction improvements to the aircraft. At the 1999 JTCG/AS National Man-Portable Air Defense System (MANPADS) Conference held at the Missile and Space Intelligence Center (MSIC) in Huntsville, Alabama, Joe presented a briefing on the results of these efforts, identifying AV–8B vulnerabilities to MANPADS and stressing the importance of designing vulnerability reduction into an aircraft early in the design phase. He also arranged for an AV–8B pilot, who had

been shot down in Desert Storm to talk about his real world experiences, reinforcing the importance of designing survivability into an aircraft early on.

In 1998 Joe was named as the Lead Engineer for the V–22 LFT&E Program, where he planned, coordinated, and conducted the V–22 LFT&E Program, overseeing a 12 member team of engineers and technicians in performing this program. Due to Mr. Manchor's outstanding engineering, test, and managerial capabilities, the V–22 LFT&E Program is widely recognized as one of the best LFT&E program carried out by any service to date, directly identifying vulnerability problems and new vulnerability reduction technologies to solve those problems. He reported on this program at the 2000 National Defense Industrial Association (NDIA) LFT&E Conference in Austin, Texas, presenting a paper entitled "The Importance of LFT in Ensuring an Operationally Effective Aircraft Combat Survivability Design (The V–22 Story)". Since 2000, he has also been responsible for the MH–60S/R Seahawk LFT&E Program, applying all of his experience and expertise to this new program.

Joe has also done an outstanding job in the fire suppression R&D area for both the Navy and the JTCG/AS. Since 1999, he has been the Chairman of the Naval Air Warfare Center Weapons Division's Fire Science and Technology Panel focused on improving fire science and fire protection technologies for the Navy and others. Also, since 2000, Joe has been the Chairman of the Fuel Systems Committee under the JTCG/AS Vulnerability Reduction Subgroup. This committee has developed the most innovative fire suppression projects that have been undertaken by the JTCG/AS for many years, including the Ionomer Fuel Containment Project, the Reactive Powder Panel Project (see Figures 1 & 2 below), as well as other new and exciting fire suppressions projects. Mr. Manchor reported on these projects in a well-written article entitled "New Concepts in Passive Fire Protection." in the Winter 2001/2002 issue of the JTCG/AS Newsletter.

Mr. Manchor also presented these passive fire protection concepts in an outstanding technical poster paper and exhibit at the NDIA Combat Survivability Division's Survivability Symposium held on 5–8 November 2001 at the Naval Postgraduate School in Monterey, California, where he won the Best Technical Exhibit Award. Mr. Manchor's paper was selected by the Combat Survivability Division's Executive Board based on depth of research, timeliness and applicability of material, display appearance, and the author's overall knowledge of the subject. The award was presented by RADM Robert Gormley, USN (ret.), the Chairman of the NDIA's Combat Survivability Division.

Mr. Manchor receiving the "Best Technical Exhibit Award" from RADM Robert Gormely.

Mr. Manchor has been married for 16 years to his lovely wife, Dory. Hobbies and interests include camping in the Sierra Mountains, free flight model airplanes, on-line video games, and "risk management training" visits to nearby Las Vegas. It is with great pleasure that we present Mr. Joe Manchor as the first JTCG/AS Young Engineer in Survivability. ◆

Figure 1. Standard Fire Protection Powder Panel provides only limited protection due to the small amount of fire suppression powder released by ballistic impact.

Figure 2. Prototype Reactive Powder Panel with Energetic Enhancement. Ballistic impact releases all of the encased fire suppression powder from the panel. This new concept promises greatly enhanced fire protection over the standard powder panel shown in Figure 1.

calendar of events

JUN

4–6—Monterey, CA
IRCM Symposium, Naval Postgraduate School
Contact: IRIA: 734.994.1200,
mss@veridian.com
www.iriacenter.org

16–21—Worcester, MA
7th International Symposium on Fire Safety Science
Contact: IAFSS Conference, 508.831.622,
IAFSS@wpi.edu
www.wpi.edu/+IAFSS

25–28—Colorado Springs, CO
Joint Model Users Meeting (JMUM)
Contact: Paul Jeng, 937.431.2712

JUL

9–11—Lake Buena Vista, FL
Unmanned Systems 2002
www.auvsi.org

NOV

4–8—Dayton, OH
Aircraft Fire Protection/Mishap Investigation Course
members.aol.com/afp1fire/www.htm

Information for inclusion in the
Calendar of Events may be sent to:

SURVIAC, Washington Satellite Office
Attn: Christina McNemar
3190 Fairview Park Drive, 9th Floor
Falls Church, VA 22042
PHONE: 703.289.5464
FAX: 703.289.5467

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